Pathways to Carbon Neutrality in the United States: Evaluating Private AI Investment, Financial Development, and Macroeconomic Forces

Amerika Birleşik Devletleri'nde Karbon Nötrlüğüne Giden Yollar: Özel Yapay Zeka Yatırımlarının, Finansal Gelişmenin ve Makroekonomik Güçlerin Değerlendirilmesi

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ABSTRACT

This study analyzes the impact of private investment in artificial intelligence (PAI) and financial development (FD) on carbon dioxide (CO_2) emissions in the United States as well as the contribution of foreign direct investment (FDI), economic growth, and population growth. The analysis uses the annual data of 1996-2022 to test the short- and long-run dynamics using the STIRPAT framework with the ARDL bounds testing technique. The ARDL methodology is confirmed through unit root analyses, which support the presence of a mixed-order integration. The findings indicate that GDP, FDI, and population growth serve as principal factors influencing CO2 emissions in both the short and long term, thereby suggesting that environmental pressures persist amidst economic and demographic progression. In contrast, PAI has a negative and statistically significant impact on emissions, which underscores the prospects of developed technologies to increase energy efficiency and contribute to environmental sustainability. FD also helps minimize emissions in the long run, which highlights the beneficial impact of financial systems in facilitating cleaner patterns of investment. Further, the results of Granger causality indicate numerous unidirectional relationships, especially between GDP, PAI, FDI, population and CO_2 emissions.

ÖZET

Bu çalışma, özel yapay zekâya yatırımların (ÖYZ) ve finansal kalkınmanın (FK) Amerika Birleşik Devletleri'ndeki karbondioksit (CO_2) emisyonları üzerindeki etkisini ve ayrıca yabancı doğrudan yatırımın (DYY), ekonomik büyümenin ve nüfus artışının katkısını analiz etmektedir. Analiz, 1996-2022 yılları arasındaki yıllık verileri kullanarak, ARDL sınır testi tekniği ile STIRPAT çerçevesini kullanarak kısa ve uzun vadeli dinamikleri test etmektedir. ARDL metodolojisi, karma dereceli entegrasyonun varlığını destekleyen birim kök analizleri ile doğrulanmıştır. Bulgular, GSYİH, DYY ve nüfus artışının hem kısa hem de uzun vadede CO_2 emisyonlarını etkileyen temel faktörler olduğunu ve böylece ekonomik ve demografik ilerlemeye rağmen çevresel baskıların devam ettiğini göstermektedir. Buna karşılık, ÖYZ'nin emisyonlar üzerinde negatif ve istatistiksel olarak anlamlı bir etkisi vardır; bu da gelişmiş teknolojilerin enerji verimliliğini artırma ve çevresel sürdürülebilirliğe katkıda bulunma potansiyelini vurgulamaktadır. FK ayrıca uzun vadede emisyonları en aza indirmeye yardımcı olur; bu da finansal sistemlerin daha temiz yatırım modellerini kolaylaştırmadaki faydalı etkisini vurgulamaktadır. Ayrıca, Granger nedensellik analizinin sonuçları, özellikle GSYİH, ÖYZ, DYY, nüfus ve CO_2 emisyonları arasında çok sayıda tek yönlü ilişki olduğunu göstermektedir.

1. INTRODUCTION

In recent years, the concepts of "banking and digitalization" have gained increasing importance in parallel with rapidly advancing technology and changing societal needs. Scientific and technological advancements have not only introduced new possibilities but also made fundamental changes in many sectors. Following the widespread use of the internet, concepts such as cloud technologies, artificial intelligence, the Internet of Things (IoT), augmented reality and virtual reality have entered our lives and the banking sector has also been affected by this digital transformation process.

With increasing awareness of the rising rate of global warming, environmental sustainability has become one of the main subjects of debate in modern economic and policy discourses. A large body of research has emphasized that rapid industrial expansion, urbanization, and intensified resource extraction have significantly altered ecological systems, driving a sustained increase in carbon dioxide (CO_2) concentrations worldwide (Abid et al., 2022; Mehmood & Tariq, 2020). As the most popular and familiar measure of environmental deterioration, CO_2 emissions reflect the magnitude of human-driven stress on natural ecosystems (Tiba & Omri, 2017; Voumik et al., 2024). The necessity to limit the temperature increase to less than 2°C, and preferably less than 1.5°C but not more, is emphasized by international agreements such as the Paris Accord, which warns that the failure to implement sufficient mitigation will lead to devastating social and economic effects (UN, 2017; Ridwan et al., 2024). In recent decades, technological advancements have emerged as both a source of environmental strain and a potential instrument for mitigation. Although industrial systems have contributed substantially to rising emissions, innovations in clean technologies, artificial intelligence, and energy-efficient production offer promising avenues for carbon reduction. Emerging studies have highlighted the capacity of advanced digital tools to enhance environmental monitoring, optimize energy use, and support low-carbon transitions (Nassef et al., 2023). Simultaneously, the global shift toward knowledge-intensive economic activity has intensified interest in identifying how new technological and financial mechanisms shape environmental outcomes. Against this backdrop, understanding the multifaceted drivers of CO_2 emissions is crucial for designing effective and sustainable climate policies.

Because of its large economy, advanced technology, and history of high greenhouse gas emissions, the United States is the focus of global climate change talks around the world. The US is one of the largest carbon emitters in the developed world. This means that the US's environmental future has a significant impact on global efforts to reduce carbon emissions (British Petroleum, 2022; World Bank, 2022). The US Environmental Protection Agency (EPA) stated that, in 2018, carbon dioxide accounted for more than 81% of all greenhouse gas emissions. Industrial processes alone account for almost a quarter of these emissions (US EPA, 2020; US EIA, 2020). The country saw strong GDP growth, with a 19% increase from 2007 to 2016; however, the separation of economic growth from emissions is still incomplete, which shows that structural pressures are still present (Wang et al., 2019). The US government has recognized these difficulties and renewed its commitment to being carbon-neutral. This includes the Clean Energy Revolution and Environmental Justice Plan, which outlines a plan to achieve a 100% clean-energy economy and net-zero emissions by 2050 (Harris, 2020). State-level initiatives bolster these national goals by increasingly focusing on expediting the adoption of renewable energy, improving technological efficiency, and integrating more intelligent industrial systems (Dehdar et al., 2023). In this context, it is important to know the causes of CO_2 emissions in the US This is important for both the national climate policy and global efforts to promote sustainable development.

To comprehend CO emissions in the United States, it is necessary to take a closer look at a number of financial, technological, and demographic forces that independently affect environmental performance. Economic activity is also an important factor of carbon intensity, and a number of studies indicate that increasing GDP increases energy demand and industrial production, which raises emissions (Raihan et al., 2022; Ahmad et al., 2024). Technological development, particularly the use of artificial intelligence (PAI) by individuals, may also reduce environmental pressure by improving efficiency, energy consumption, and monitoring. (Delanoë et al., 2023; Dong et al., 2023; Liu et al., 2022). Financial development (FD) operates in a dual capacity; it can facilitate green innovation and low-carbon investments through advanced financial mechanisms, while simultaneously fostering consumption patterns that may escalate emissions, contingent upon specific conditions (Zafar et al., 2019; Mehmood, 2024). Foreign direct investment (FDI) presents challenges, as it can either introduce cleaner technologies or exacerbate pollution-intensive production (Shahbaz et al., 2019; Balli et al., 2023). The increase in population intensifies environmental pressure by elevating energy demand and resource consumption, as evidenced by recent studies across various economies (Voumik et al., 2023a; Pachiyappan et al., 2021). The interdependent variables underscore the necessity of a cohesive empirical model to elucidate the collective influence of these factors on US emissions.

Despite extensive literature examining the determinants of environmental degradation, significant gaps remain concerning the combined influence of technological advancement, financial structures, and macroeconomic forces on US carbon emissions. While earlier studies investigated the roles of GDP, population growth, financial improvement, and foreign direct investment independently or within broader multi-country samples, their findings often present conflicting evidence, particularly regarding the environmental implications of FD and FDI (Zafar et al., 2019a; Suhrab et al., 2023; Salahuddin et al., 2018). Moreover, the environmental impact of private investment in artificial intelligence (PAI) has received limited empirical attention, even though recent studies highlight artificial intelligence as a powerful driver of efficiency improvement and emission reduction (Delanoë et al., 2023; Liu et al., 2022). The existing literature also lacks a focused country-specific assessment for the United States that incorporates PAI alongside FD, FDI, GDP, and population within a unified analytical framework. Given a country's substantial economic scale, technological leadership, and strategic commitment to achieving carbon neutrality, such an assessment is crucial. Additionally, very few studies employ the STIRPAT model in combination with ARDL techniques to explore both short- and long-run dynamics in the US context. This study addresses these gaps by developing a comprehensive empirical approach to uncover the key drivers shaping a nation's emissions trajectory.

This study offers an in-depth evaluation of the factors that influence carbon dioxide emissions in the US through the synthesis of economic, technological, financial, and demographic elements in a single empirical model. Specifically, it examines the role of private investment in artificial intelligence (PAI), financial development (FD), foreign direct investment (FDI), economic growth, and population growth in encouraging CO_2 emissions in the short and long run. Based on the STIRPAT model as a theoretical base and the ARDL bounds-testing method as an empirical estimation, this study aims to capture dynamic adjustments, cointegration relationships, and convergence speed in the US profile of emissions. The contributions of this study are fourfold: First, it introduces PAI as a key technological indicator, addressing the limited empirical attention given to AI-driven investments in environmental studies. Second, it provides updated and country-specific evidence using annual data from 1996 to 2022, offering more recent insights than many existing studies. Third, this study incorporates financial development and FDI simultaneously, helping to clarify their often-contradictory roles in environmental outcomes. Fourth, employing Granger causality tests uncovers directional linkages among variables, providing policymakers with actionable guidance for designing technology-driven and finance-supported climate strategies. Collectively, these contributions strengthen the understanding of the pathways through which the United States can advance toward carbon-neutral development.

2. LITERATURE REVIEW

A substantial body of literature has examined the correlation between economic growth and environmental degradation, yet the findings remain inconclusive. Numerous studies have indicated that an increase in GDP leads to a higher level of CO_2 emission owing to the growth in energy demand, industrial production, and consumption of resources (Raihan et al., 2022; Ahmad et al., 2024; Pattak et al., 2023). This pattern is particularly evident in rapidly expanding economies, where growth is closely tied to fossil fuel use, creating direct and persistent upward pressure on emissions. However, the empirical evidence is not universally aligned with this interpretation. Some studies suggest that economic growth may contribute to emission reductions under certain structural or technological conditions by facilitating cleaner production, efficiency improvements, and investments in low-carbon technologies (Raihan et al., 2023; Mehmood et al., 2021). These disparate findings illustrate variations in national energy compositions, developmental phases, and policy structures, highlighting the necessity for country-specific evaluations. For the United States, one of the world's largest economies and energy consumers, understanding the GDP-CO_2 nexus is particularly relevant, as growth remains intertwined with technological advancement, industrial activity, and consumption patterns. Given these mixed global findings, reassessing the role of GDP within a comprehensive US-focused model is essential to clarify whether economic expansion continues to exacerbate emissions or to support pathways to decoupling.

Technological innovation has become a central mechanism for mitigating environmental degradation, with recent studies emphasizing the ability of advanced digital tools to enhance energy efficiency and reduce carbon intensity. In particular, artificial intelligence (AI) has shown a significant possibility of optimizing industrial work, advancing monitoring systems, and making it possible to allocate energy and resources more efficiently (Delanoë et al., 2023; Dong et al., 2023). In China, empirical data indicate that AI implementation and technological upgrades based on robotics can substantially reduce emissions by changing production formats and boosting low-carbon performance (Chen et al., 2022; Liu et al., 2022). Machine learning applications have also been shown to support pollution prediction and real-time environmental management, contributing to broader sustainability

objectives (Zhao et al., 2023). Despite these advances, limited empirical research evaluates the environmental effects of private investment in AI, particularly in advanced economies such as the United States. This gap highlights the need for a focused analysis to determine whether technology-driven investments can meaningfully contribute to long-term emissions reduction.

One of the most discussed issues in sustainability studies is the connection between financial development (FD) and environmental quality. According to several studies, more developed financial systems spur economic activity, credit growth, and consumption, leading to increased energy consumption and CO_2 emissions, especially in emerging and middle-income economies (Rjoub et al., 2021; Suhrab et al., 2023). However, other studies indicate that FD may also promote cleaner production through investments in technologies with low carbon content, higher efficiency in the allocation of capital, and environmentally responsible industries (Tamazian & Rao, 2010; Zafar et al., 2019; Mehmood, 2024). These conflicting findings highlight the dual nature of financial development, which may intensify environmental pressure or promote green transformation, depending on institutional quality, credit structure, and policy design. For advanced economies, such as the United States, where financial markets are highly sophisticated, the role of FD may differ substantially from patterns observed in developing regions. This raises the need for context-specific examination of whether financial expansion strengthens or weakens environmental sustainability.

Foreign direct investment (FDI) influences environmental outcomes through two competing channels, resulting in mixed empirical evidence across global studies. According to the pollution halo approach, FDI may lead to a decrease in emissions due to the introduction of cleaner technology, an increase in managerial efficiency, and innovation spillovers, which positively influence the environmental performance of host countries (Zhu et al., 2018; Lahiani, 2020; Saadaoui et al., 2024). On the other hand, the pollution haven hypothesis posits that FDI can further increase emissions as multinational companies transfer pollution-intensive sectors to areas with weaker regulations and contend that resources are used inefficiently, leading to pollution (Baloch et al., 2019; Yang et al., 2020; Salahuddin et al., 2018). These contrasting results underscore the context dependence of FDI's environmental impact, shaped by regulatory frameworks, technological absorption capacity, and industrial composition. For the United States, a technologically advanced and highly regulated economy, evaluating whether FDI promotes cleaner production or amplifies carbon intensity remains crucial for understanding its role in long-term sustainability.

Population growth is widely regarded as a fundamental determinant of environmental pressure, as expanding populations increase energy demand, urbanization, and resource consumption. Numerous studies confirm that higher population levels are closely associated with rising CO_2 emissions, particularly in developing and rapidly growing economies, where demographic expansion directly amplifies environmental stress (Voumik et al., 2023a; Pachiyappan et al., 2021). Evidence from Argentina, Kenya, and SAARC countries demonstrates that population increases significantly contribute to long-term ecological degradation (Voumik & Ridwan, 2023; Anser et al., 2020). Nevertheless, certain sources indicate that the relationship between population and emissions can be moderated by structural variations, energy compositions, and policy conditions, which may be insignificant or mixed (Alam et al., 2016; Begum et al., 2015). These divergent findings underscore the need to re-examine demographic impacts in advanced economies, such as the United States, where population growth interacts with high per-capita energy use, technological change, and evolving consumption patterns.

Although extensive research has explored the roles of GDP, population growth, financial development, and FDI in shaping CO_2 emissions, their combined influence remains insufficiently examined within a US-specific context. Existing studies offer conflicting evidence on whether FD and FDI mitigate or intensify environmental degradation. Moreover, the environmental implications of private investment in artificial intelligence (PAI) remain largely unexplored despite growing evidence that AI-driven innovation can significantly reduce emissions. No current research combines GDP, PAI, FD, FDI, and POP within a cohesive STIRPAT-ARDL framework for the United States, thereby establishing a distinct empirical void that this study aims to fill.

3. METHODOLOGY

This study uses annual time-series data for the United States between 1996-2022 to investigate the determinants of CO_2 emissions as part of the STIRPAT model. CO_2 emissions, sourced from the Global Footprint Network, serve as the dependent variable. Private investment in artificial intelligence (PAI) is obtained from Our World in Data, reflecting technological advancement. Financial development (FD) is calculated using the IMF Financial Development Index. The World Development Indicators provide data on foreign direct investment (FDI), GDP

per capita, and total population. All variables are converted to natural logarithms to make the scales consistent and minimize heteroscedasticity during the estimation.

This study applied a simplified version of the STIRPAT model to analyze the drivers of CO_2 emissions in the United States. STIRPAT goes beyond the conventional IPAT identity by providing a stochastic and adaptable framework according to which environmental pressure can be estimated as a population, affluence, and technology-dependent function. The model effectively captures the structural and technological impacts on emissions by introducing economic activity (GDP), financial development, foreign direct investment, population size, and the size and nature of private investment in AI. Logarithmic transformation was used to linearize relationships and reduce data variability, enabling a more robust assessment of how these factors shape environmental outcomes. The STIRPAT format is as follows:

$$I_{it} = C P_{it}^{\gamma_1} A_{it}^{\gamma_2} T_{it}^{\gamma_3} \varepsilon_{it} \tag{1}$$

Here, P refers to the population of country A to its wealth and T to its technology at time t. In the STIRPAT model, C is a constant term, and ε is a random error element.

The logarithmic transformation of the model may be expressed as follows:

$$LnI_{it} = C + \gamma_1 lnP_{it} + \gamma_2 lnA_{it} + \gamma_3 lnT_{it} + \varepsilon_{it} \tag{2}$$

Our research variables were CO_2 emission as an expression of impact (I); population growth as an indicator of population (P); affluence (measured by GDP, FD, and FDI); and technological level (measured by private investment in AI). An experimental realization of the mathematical framework relying on the applicable literature available at present was obtained as follows:

$$CO_2 = f(GDP_{it}, PAI_{it}, FD_{it}, FDI_{it}, POP_{it}) \tag{3}$$

GDP, PAI, FD, FDI, and POP are taken as the explanatory variables in this case, and the dependent variable is CO_2. Unlike the results obtained using linear models, log transformations yield more precise and effective results. The empirical model can be explained as follows:

$$lnCO_{2_{it}} = \beta_0 + \beta_1 lnGDP_{it} + \beta_2 lnPAI_{it} + \beta_3 lnFD_{it} + \beta_4 lnFDI_{it} + \beta_5 lnPOP_{it} + \varepsilon_{it} \tag{4}$$

where β_0 is the intercept, and β_1 to β_5 are the coefficients of the independent variables selected. The natural log and error term of the model are represented by the letters ε and L, respectively, and appear at the beginning of the equation.

This study employs an extended STIRPAT framework to quantify how economic, technological, financial, and demographic factors influence CO_2 emissions in the United States. The model is in log-linear form, where the coefficients may be interpreted as elasticities, reduce variance, and enhance estimation stability. Before the model estimation, unit root tests are used to confirm the order of integration of each variable, and none of them has an order of integration greater than I(1), which is a precondition for using the ARDL approach. The ARDL method is chosen because it supports regressors of mixed integration and captures short-run adjustments and long-run equilibrium dynamics. To ascertain the existence of a stable long-run relationship between CO_2 emissions and their determinants, a bounds-testing procedure was initially employed. After a cointegration test has been passed, long-run parameters are estimated, and an error-correction model is used to examine short-run impacts and the rate at which equilibrium distortions are fixed. In addition, pairwise Granger causality tests are implemented to determine the directional relationships of the variables, which will provide information about whether the shift in emissions will be preceded by the change in economic activity, technological investment, financial development, or demographic patterns in systematic ways.

4. RESULTS AND DISCUSSION

The descriptive statistics are shown in Table 1 illustrate the updated details of the main factors used in the analysis, demonstrating meaningful variation across economic, technological, financial, and demographic indicators in the United States. LCO₂ displays relatively low dispersion, suggesting stable emission patterns over time, while LGDP and LPAI show wider variability, which is consistent with economic fluctuations and evolving

technological investments. The distributional properties reveal mild skewness across most variables, with the LPAI exhibiting a positive skew due to rising AI-related spending in recent years. Overall, the revised statistics confirm balanced data behavior suitable for time-series estimation within the STIRPAT-ARDL framework.

Table 1. Summary Statistics

Variable	Mean	Median	Maximum	Minimum	Std. Dev.	Skewness	Kurtosis
LCO_2	15.472	15.460	15.585	15.295	0.082	-0.452	2.601
LGDP	10.658	10.732	11.172	10.095	0.322	-0.241	1.912
LPAI	22.105	21.310	25.742	20.632	1.689	1.012	2.488
LFD	-0.159	-0.091	-0.075	-0.501	0.134	-1.641	4.221
LFDI	25.944	26.120	26.982	24.201	0.771	-0.701	2.590
LPOP	19.512	19.520	19.631	19.349	0.087	-0.301	1.904

The unit root findings in Table 2 affirm that the variables follow a mixed integration pattern, justifying the use of the ARDL framework. The majority of the variables, such as CO_2 emissions, GDP, private AI investment, financial development, and foreign direct investment, are non-stationary at level but are stationary after the first differencing and are of I(1) nature. In contrast, the population remains stationary at the level across all tests, reflecting its stable long-term trajectory in the United States. The reliability of the findings was enhanced by the consistency of the ADF, PP, and DF-GLS tests. The mixed order of integration supports the ARDL bounds-testing method in the analysis of long-run correlations between the variables.

Table 2. Unit Root Test

Variable	ADF I(0)	ADF I(1)	PP I(0)	PP I(1)	DF-GLS I(0)	DF-GLS I(1)
LCO_2	-0.210	-5.102***	-0.398	-5.088***	-0.545	-4.120***
LGDP	-0.925	-4.910***	-1.010	-4.892***	-0.901	-4.150***
LPAI	-0.740	-7.602***	-1.821	-7.520***	-0.622	-6.255***
LFD	-2.680	-4.451***	-2.045	-4.620***	-1.822	-4.702***
LFDI	-1.710	-6.620***	-1.540	-6.700***	-0.691	-4.930***
LPOP	-4.820***	-7.910***	-6.720***	-8.632***	-3.790***	-5.810***

Note: 1% significance level is denoted by ***.

The regenerated ARDL bounds test results provide evidence of the existence of a stable long-run relationship between CO_2 emissions and its most important determinants. According to Table 3, the calculated F-statistic of 4.382 is greater than the upper critical value at the 5% level of significance, which proves the cointegration using the ARDL model. This means that the variables, which include GDP, private investment in AI, financial development, foreign direct investment, and population change together in the long run, although they may vary in the short run. To justify the ensuing long-run and short-run ARDL estimations, it is necessary to establish cointegration, which means that the system will reach equilibrium in the long run. These results confirm the need to conduct a complete ARDL analysis.

Table 3. ARDL Bound Test

Test Statistic	Value	Significance Level	Critical Values (I0 / I1)
F-statistic	4.382	10%	2.10 / 3.05
		5%	2.42 / 3.45
		2.5%	2.73 / 3.80
		1%	3.12 / 4.20

The ARDL results show that GDP exerts a positive and statistically significant impact on CO_2 emissions in both the long and the short run. In the long run, a 1% rise in GDP increases emissions by approximately 0.048%, indicating that sustained economic expansion continues to increase energy use and industrial activity. The short-run coefficient (0.039%) also confirms an immediate emission response to economic growth, reflecting the US economy's dependence on energy-intensive production structures. This finding is consistent with many studies that have documented the ecological impact of output growth, including Raihan et al. (2022), Ahmad et al. (2024), and Pattak et al. (2023), all of whom have observed that increased economic activity increases carbon intensity in both advanced and emerging economies. This positive association is also consistent with long-standing empirical evidence showing that increased demand for goods, services, and transportation drives greater fossil-fuel consumption (Mehmood & Tariq, 2020). Although some studies note potential decoupling under advanced

technological transitions (Raihan et al., 2023), the current findings suggest that the US economy has not fully achieved such a structural transformation, and output growth remains closely tied to higher emissions.

The ARDL estimates reveal that private investment in artificial intelligence (PAI) significantly reduces CO_2 emissions in both horizons. In the long run, a 1% increase in PAI lowers emissions by 0.061%, whereas the short-run coefficient (–0.025%) confirms an immediate reduction effect. These results indicate that AI-driven technological upgrading enhances energy efficiency, optimizes production processes, and strengthens environmental monitoring systems. Such improvements allow firms to adopt cleaner technologies, reduce waste, and shift toward more sustainable operational practices. This observation is well grounded in the literature: Delanoë et al. (2023) provide evidence that AI models can optimize carbon-management policies; Dong et al. (2023) state that AI can lower emissions by changing industrial structures; and Liu et al. (2022) reveal that AI can help industrialists in China to reduce their emission levels. There is also additional evidence of significant carbon intensity reduction through robotic automation (Chen et al., 2022).

Table 4. ARDL Short-Run and Long-Run Test

Variable	Coefficient	Std. Error	t-Statistic	Prob.
Long-Run Estimates				
LGDP	0.048	0.018	2.611	0.014
LPAI	-0.061	0.020	-3.050	0.006
LFD	-0.332	0.121	-2.741	0.012
LFDI	0.031	0.011	2.781	0.011
LPOP	0.298	0.142	2.099	0.043
C	10.122	4.810	3.103	0.004
Short-Run Estimates				
D(LGDP)	0.039	0.015	2.523	0.018
D(LPAI)	-0.025	0.007	-3.412	0.003
D(LFD)	0.207	0.095	2.183	0.037
D(LFDI)	0.006	0.003	2.020	0.049
D(LPOP)	0.284	0.132	2.152	0.039
CointEq(-1)	-0.462	0.102	-4.529	0.001

The ARDL findings show that financial development (FD) reduces CO_2 emissions in the long run but slightly increases them in the short run. In the long run, a 1% increase in FD lowers emissions by 0.332%, indicating that a mature financial system supports cleaner investments, enhances access to green financing, and promotes environmentally efficient technologies. However, the short-run coefficient (+0.207%) suggests temporary emission increases due to expanded credit availability, which may initially stimulate consumption, housing demand, and higher energy use, consistent with the transitional effects often observed in advanced economies. These ambiguous findings are reflected in the literature. Zafar et al. (2019) and Mehmood (2024) emphasize the role of FD in enhancing environmental quality due to the better allocation of resources and the promotion of eco-innovation, and Rjoub et al. (2021) and Suhrab et al. (2023) state that the intensification of financial activity may increase pollution rates, particularly when credit is diverted to energy-intensive industries. The US results align with both perspectives: short-run financial expansion raises emissions, but long-run financial maturity facilitates a shift toward cleaner economic structures.

According to the ARDL findings, foreign direct investment (FDI) raises CO_2 emissions in the long and short term. A long-run FDI percentage increase of 1% increases emissions by 0.031%, whereas the short-run coefficient (0.006) indicates short-term environmental strain linked to inflows of capital. This pattern indicates that in the US context, FDI tends to reinforce economic activities that are energy-intensive or reliant on existing industrial infrastructure, thereby contributing to higher carbon output. This outcome is consistent with the polluting haven hypothesis found in previous literature, in which multinational corporations grow production in a manner that increases resource consumption and emissions (Baloch et al., 2019; Yang et al., 2020; Salahuddin et al., 2018). Although some studies highlight the potential for FDI to introduce cleaner technologies (Zhu et al., 2018; Lahiani, 2020), the current findings suggest that such effects are either limited or overshadowed by scale-driven emission increases in the US economy. Overall, FDI appears to reinforce production expansion rather than green technology spillover in this context.

The ARDL estimates show that population growth significantly increases CO_2 emissions in both the long and short run. In the long run, a 1% increase in population raises emissions by 0.298%, whereas the short-run effect

(0.284%) indicates an immediate increase in environmental pressure. These results reflect the fundamental role of demographic expansion in driving energy demand, transportation needs, industrial output, and overall resource consumption in the United States. This finding is consistent with extensive empirical evidence that larger populations generate proportionately higher emissions across diverse economies. Strong, positive population-emissions relationships exist in both emerging and developing regions, according to Voumik et al. (2023a) and Pachiyappan et al. (2021). The same can be noted in the case of SAARC and African states, where population increases exacerbate environmental degradation over time (Anser et al., 2020; Voumik et al., 2023b). Although some researchers have found mixed or trivial impacts (Alam et al., 2016; Begum et al., 2015), US outcomes support the idea that population growth is one of the major structural determinants of carbon intensity, which argues in favor of sustainable urban planning and resource allocation.

The diagnosis findings in Table 5 verified that the ARDL model is highly reliable and specific. Assessment of the Breusch-Godfrey LM test indicates that there is no serial correlation, implying that lags have independent residuals. The Breusch-Pagan-Godfrey test verified that there is no heteroskedasticity, and therefore, the error variance is constant. The Jarque-Bera statistic indicates normally distributed residuals, supporting the validity of the model's inference. Further evidence of the correct specification of the functional form and absence of omitted-variable bias is the Ramsey RESET test. Figures 1 and Figure 2 illustrate the CUSUM and CUSUM Square tests, indicating the stability of the model's parameters.

Table 5. Diagnostic Test Result

Test	Statistic	Prob./Decision
Breusch–Godfrey LM (Serial Correlation)	1.482	0.242 (No serial correlation)
Breusch–Pagan–Godfrey (Heteroskedasticity)	12.911	0.381 (No heteroskedasticity)
Jarque–Bera (Normality)	1.992	0.369 (Residuals normal)
Ramsey RESET (Functional Form)	0.511	0.477 (Correct specification)

Figure 2. CUSUM Test

Figure 3. $CUSUM^2$ Test
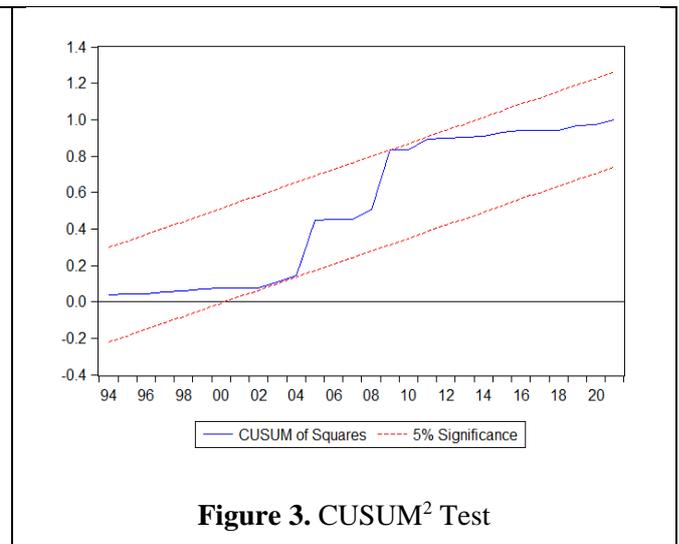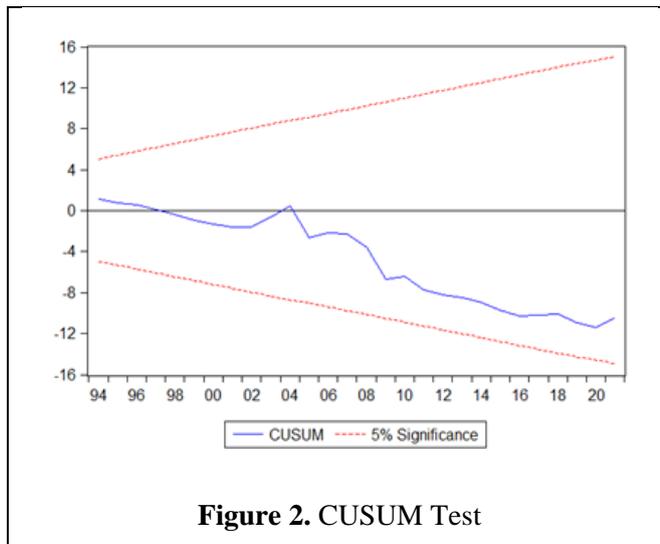
5. CONCLUSION

This study aims to provide an in-depth analysis of the main causes of CO_2 emissions in the United States by combining economic, technological, financial, and demographic variables in a longer STIRPAT-ARDL model. These findings confirm the existence of a stable long-run equilibrium relationship between emissions and their determinants. The findings revealed that economic growth, foreign direct investment, and population growth continued to increase the environmental pressure. These findings highlight the continued dependence of the US economy on energy-intensive activities, despite advancements in industrial efficiency. In contrast, private investment in artificial intelligence emerged as an effective mechanism for reducing emissions, underscoring the transformative potential of technology-driven innovation. Financial development also contributes to long-term emission reductions, although its short-run effects indicate transitional pressures associated with expanding credit availability. Overall, this study demonstrates that technological upgrading, strengthened financial systems, and demographic management are essential components of a sustainable transition. By identifying the channels

through which these factors influence carbon dynamics, this study offers valuable insights for designing targeted policies that support the nation's carbon neutrality pathway. Thus, future environmental planning should prioritize AI-driven innovation, green financial instruments, and responsible investment flows to accelerate low-carbon development in the United States.

The results of this study present a number of valuable policy implications for enhancing the process of low carbonization in the United States economy. First, the significant emission-reducing effect of private AI investment highlights the need for policies that expand digital innovation, support AI-driven industrial automation, and incentivize firms to adopt advanced monitoring and energy-efficient technologies. Targeted tax credits, AI innovation grants, and public–private technology partnerships can accelerate these gains. Second, financial development has a long-run impact, which indicates that capital can be allocated to lower carbon production and the implementation of renewable energy by reinforcing green finance markets such as green bonds, sustainability-linked loans, and climate-risk disclosure frameworks. Financial regulators should encourage financial institutions to incorporate environmental risk into lending activities and increase incentives to have environmentally responsible investment portfolios. Third, the positive correlation between FDI and emissions suggests a need to tighten the environmental screening of incoming investments. Establishing minimum environmental performance standards for multinational firms and prioritizing technology-intensive low-carbon FDI can help reverse pollution-haven tendencies. Fourth, sustained economic growth continues to elevate emissions, reinforcing the need for structural reforms that decouple output expansion from fossil fuel dependence. This includes modernizing industrial processes, tightening energy-efficiency standards, and scaling up the renewable energy capacity. Finally, population-driven emission pressures require policies that promote sustainable urbanization, low-carbon transport networks, and resource-efficient housing development. Collectively, these measures demonstrate that coordinated action across technological, financial, regulatory, and urban planning domains is essential for achieving long-term carbon neutrality in the United States.

Despite important insights into the determinants of CO_2 emissions in the United States, this study has several limitations. The time-series data used in the analysis include annual data, and such data might not be effective in capturing the short-term and sector-specific dynamics that can affect emissions. Additionally, the use of aggregate indicators for financial development, AI investment, and FDI may obscure important differences between industries and states. The model also focuses on linear relationships, while emerging evidence suggests that environmental responses may exhibit nonlinear or threshold effects. Future studies can fill these gaps by using higher-frequency or sector-disaggregated data, non-linear modelling methods, and non-linear modelling by adding other technological or institutional factors. Comparative studies across advanced economies can also offer a deeper understanding of how structural and policy differences shape carbon outcomes.

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The entire research is written by the author.

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